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FUEL BEHAVIOUR AFTER A LOCA FOLLOWED BY A SITE DESIGN EARTHQUAKE AT 24 HOURS AFTER THE INITIAL EVENT

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ABSTRACT - Following a LOCA event, the long term decay power removal is ensured by low pressure ECC pumped flow. As per design, a Site Design Earthquake (SDE) can occur at 24 h after the initial assumed event. The paper will present the main results related to broken loop fuel behaviour following such a sequence of events.

Keywords: Loss Of Coolant Accident (LOCA); Emergency Core Cooling system (ECC); Site Design Earthquake (SDE).

Introduction

As per plant design, a Site Design Earthquake (SDE) can be credited to occur at 24 hours after a LOCA initiating event. As a direct results of this supplementary event, both class IV and class III electrical power supply are assumed to be lost, disabling the cooling system (ECC) operation. Emergency electrical power supply restoration can be credited at 30 minutes after a SDE event. The ECC pump operation can be credited once the emergency power supply is restored. During the time interval between the loss of class IV and III electrical power and start of the emergency electrical power system, forced core cooling will be lost. Even the decay power is small at 24 hours after reactor shutdown, the fuel cooling may be affected and supplementary fission products may be released in case of fuel failure.

The paper will present the evaluation of the fuel cooling in the absence of the ECC forced flow in the broken loop for a 30 minutes interval at 24 hours after the LOCA initiating event.

1. Event Sequence and Fuel Behaviour Presentation

A Large LOCA event is a design basis event for each nuclear power plant and a set of systems and components are incorporated in the plant design in order to limit the consequences following such an initiating event.

Following a Large LOCA event,the decay power removal will be provided by the ECC system. Initial fuel cooling is provided by the high and medium pressure ECC stages. The transfer to low pressure stage is expected after about 15 minutes from the event and represent the long term decay power heat removal for the broken loop.

During the ECC low pressure stage operation, the decay heat will be discharged in the reactor building sump and the heat accumulated will be removed by ECC heat exchanger to the ultimate heat sink. Fuel cooling in the intact loop will be provided by thermosyphoning, with heat removal through the steam generators to environment. Steam generators will be supplied with water from the feedwater train at a rate required to ensure adequate steam generators level. In the long term, the steam generators feedwater inventory will be provided by water from the feedwater train or from the emergency water supply.

As per plant design requirements, the low pressure ECC stage has to operate at least 3 months after an initiating event such as a Large LOCA, with interruptions no longer than 30 minutes. For the present analysis, at 24 hours after the initiating event, a failure of the ECC running pump is assumed to occur and no restart of the stand-by ECC pump is assumed (in order to simulate the SDE possible effects).

After the ECC pump stops, forced cooling flow through PHT broken loop will be lost. In the same time, water inventory will continue to be dischargedfrom the broken loop through the break. Due to primary heat transport system inventory discharge, the pressure in the steam generators top U-tubes will start to decrease since there is no forced flow present. The broken loop hydraulic resistances and the pressure conditions from the top U-tubes will counteract inventory loss and the flow through the break. Finally, the flow through the circuit will be significantly reduced. After the ECC pump flow stops completely, the flow through the individual channels will be generated by the inertia while the primary side of the steam generators will start to empty. However, the elevation difference, pressure and hydraulic resistances of different components from the broken loop may generate a stagnant flows in broken loop core passes.Stagnant conditions may be also expected for individual fuel channels after the primary side inventory from steam generators is lost.

In case that flow is stagnant in one individual fuel channel, the fluid temperature in that channel will start to increase and boiling conditions will be reached locally. The amount of steam accumulated in the fuel channel will increase in time. Consequently, the fuel sheath and pressure tube cooling will be degraded and, consequently, the temperatures will start to increase. Fuel integrity will be affected by the maximum temperature and the duration of these severe conditions (part of the fuel bundle cooled by steam).

The steam from the affected channel will be partially condensed but finally it will reach the colder end fitting. The fluid temperature from the end fitting and the end fitting metal will reach higher temperatures and the efficiency of the condensation process will be reduced. At that moment, the steam will escape from that fuel channel through one feeder to one of the reactor headers. Due to buoyancy difference in the feeders, the respective channel will be refilled by the sub cooled water coming from one of the reactor headers. The fuel and the pressure tube will be cooled by the colder flow entering the fuel channel.

Entire het-up and refilling process may be repeated until the forced core cooling is restored. Once the core forced flow is restored, the fuel sheath and pressure tube temperatures are expected to reach similar values to those observed during the normal low pressure ECC stage operation.

Adequate long term core cooling is expected once the ECC pump is running and heat removal from ECC heat exchanger is ensured.

2. Model Presentation

2.1 Overall model presentation

Cernavoda NPP overall circuit model has been used as the reference model for these calculations. The model includes representation of the primary circuit components with 7 average channels per each core pass, secondary circuit consisting of steam generators and feedwater train, all ECC stages and specific plant controllers.

The corresponding decay power at one day after reactor trip is included, being similar for both primary heat transport loops.

The inlet header critical break has been considered because the number of failed fuel elements is minimal before the subsequent failure (SDE event at 24 hours). For this break, any supplementary fuel failures will determine the maximum percentage of increase in the fission product releases. If fuel sheath failure would be predicted, then the maximum releases have to be considered for each of the other possible break locations because the long term behaviour of the broken loop is similar during the low pressure ECC stage operation.

For this specific sequence, the following changes have been implemented in the overall circuit:

- The analyses of the critical break in the inlet header was extended for one more hour after SDE in order to cover failure and recovery phases of ECC pump. Additional 30 minutes have been considered in order to demonstrate that steady conditions have been reached, after the ECC pump was restarted.

- The decay power at 1 day after the event was maintained constant over the duration of the analyses performed. One hour time interval is a relatively short interval in terms of decay power reduction. In the same time, higher the power, higher fuel sheath temperatures was expected.

- The maximum time interval (30 minutes) for ECC pump restart on emergency electrical power supply was considered.

- Following SDE, the secondary side feedwater supply is lost to both loops. Emergency water supply is assumed available at 30 minutes after the SDE event.

- Sensitivity cases on ECC low pressure stage fluid temperature have been considered. The initial fuel sheath and fuel channel temperaturesmay have a direct impact on the duration of the heating up process.

For each case, the circuit model was run for 25 hours from the initial event in order to obtain the header boundary conditions.

2.2 Single channel model presentation

In order to evaluate the single fuel channel behaviour, the circuit header boundary conditions have been imposed to the single channel models. A generic single channel model is presented in Figure 1.

The model has been used to evaluate the fuel sheath and pressure tube temperature evolution. The same boundary conditions have been applied to other single channel models in order to evaluate the effect of different fuel channel elevation and the effect of the hydrostatic pressure in the feeders.

2.3 Fuel channel analyses

Following loss of forced circulation, fuel sheath and fuel channel temperature will start to increase, finally boiling the liquid from the affected channel. Due to degraded cooling, steam is expected and fuel sheath temperature will increase.

Since there is a long time since theinitiatingLOCA event until the subsequent failure (SDE), the fuel sheath behaviour has been evaluated considering the following criteria:

- Fuel centerline melting - not expected because the neutron flux power is low, reactor being shutdown for a long time;
- Fuel sheath melting - correlated to fuel sheath temperature;
- Excessive diametral strain - correlated to fuel sheath temperature;
- Significant cracks in the oxide surface;
- Oxygen embrittlement;
- Sheath failure by beryllium-braze penetration.

3. Results Presentation

3.1 General considerations regarding heat sinks

Due to loss of electrical power supply following SDE event, primary heat transport system cooling will be affected. The feedwater flow supplyto steam generators will be interrupted. However, since the feedwater flow was available before, it is assumed there is a significant water inventory in the steam generators secondary side (both for the intact and broken loop), according to abnormal operating procedure requirements. For the intact loop, the fuel cooling will continue due to thermosyphoning process and heat will be removed through the steam generators. The secondary side inventory should be enough for decay power removal.

For the broken loop, due to SDE, the primary heat transport forced cooling will be lost. Continue inventory loss through the break will deplete the steam generator inventory on the primary side and will disable any heat removal through the steam generators.

The parameters of direct interest for the present type of transient are: fuel sheath temperature, pressure tube temperature and header boundary conditions. Fuel sheath temperature obtained from circuit analyses is used as an indication of the cooling process. However, header boundary conditions have been used in the single channel analyses to determine the fuel sheath and pressure tube temperatures for the individual fuel channels.

Two sets of initial ECC cooling temperature conditions have been considered. The difference was determined by the uncertainties and margins considered in the analyses.

3.2 Reference temperature for low pressure ECC stage of 55^{0}C

At one day after a Large LOCA event, because the decay power is low, it is expected that the fuel sheath and pressure tube temperatures are close to coolant temperature (as it is injected by ECC pump). For the present case, a temperature of 55^{0}C (analyses value) is assumed. Loss of forced core flow due to loss of ECC pumps will not affect the thermosyphoning process for the intact loop. The process will continue and its efficiency will be determined by the temperature difference between the cold and respectively hot leg in the intact loop steam generators.

The conditions in the broken loop will be slightly different from those in the intact loop. The initial fuel sheath temperature at the time of SDE event is about 58^{0}C, determined by ECC injected flow of about 480 kg/s. Due to break location, the flow through core pass 3 is in the forward direction while, the flow is reversed in the fuel channels from core pass 4.

Following loss of ECC pump, the core flow is expected to be reduced to zero in about 60 seconds in core pass 4. Significant flow oscillations, generated by the primary inventory depletionare predicted, from time to time, until the ECC pump operation is restored. These oscillations are generated by the water discharged from primary circuit, while the constant flow time intervals are determined by the stagnant conditions (see Figure 2 and Figure 3). Some average channels will develop a forward flow while the rest will have a reversed flow. The maximum fuel sheath temperature from the circuit simulation (Figure 4) is about 100^0C in core pass 3. The fuel sheath temperatures predicted for core pass 4 are even lower than those predicted for core pass 3 because of the break presence.

After the ECC pump operation is restored, at 30 minutes from the SDE event, the initial primary heat transport system cooling flow directionsare restored and fuel sheath temperature reached similar values to those predicted during low pressure ECC stage operation.

Single channel analyses shows a similar behaviour in terms of fuel channel flow and sheath temperatures. As long as the forced flow is present, the fuel sheath temperature is maintained below 70^0C, slightly differing from one fuel bundle to the other. The fuel sheath temperature increases during the stagnant flow intervals and is reduced during the intervals when the flow change the direction(see Figure 5 and Figure 6). Based on the single channel predictions using the header boundary conditions from circuit run, fuel sheath is not expected to exceed 116^0C. Due to break presence, the predicted fuel sheath temperature from single channel analyses is lower in core pass 4. The pressure tube temperature are close but slightly lower that fuel sheath temperatures.

Due to low fuel sheath and pressure tube temperatures, no detailed fuel sheathe and pressure tube integrity analyses were considered necessary.

3.3 Reference temperature for low pressure ECC stage of 49^0C

In order to evaluate the effect of different initial conditions, the design temperature (49^0C) during ECC low pressure stage operation was also considered. The steady state fuel sheath temperature during low pressure ECC stage operation, at one day after the Large LOCA event was estimated in this case at 52^0C.

The general circuit behaviour following SDE event was similar to that present for the previous case. The maximum fuel sheath temperature predicted by the circuit simulation was 96^0C while from the single channel analyses a maximum value of 100^0C was predicted for a fuel channel having the maximum power during normal operating conditions.

Based on these results it was concluded that small ECC coolant temperature deviations have an insignificant effect on fuel sheath and pressure tube temperatures during such an event.

3.4 Supplementary single channel analyses

During such a transient, individual fuel channels may “see” slightly different header boundary conditions. The worst hypothetical situation that can occur on one individual fuel channel is determined by the stagnant headers conditions lasting for the entire duration of the transient. The situation was simulated through single channel analyses. The decay power, corresponding at one day after a LOCA event, was imposed and was maintained constant for the duration of the transient.

The analyses considered two sets of boundary conditions determined by a water level in the headers corresponding to 0.2 m and respectively 0.9 m. The level imposed in each header was determined in such a way to minimize the water flow through the individual fuel channel for the entire duration of the transient.

Due to stagnant conditions determined by the headers, there is no flow through the individual fuel channel. The inventory from the fuel channel will start to heat up,increasing the temperature of the respective fuel channel components. Finally, the water will start to evaporate locally and a steam volume is expected to occur in the respective fuel channel. Consequently, the fuel sheath temperature will start to increase and more steam will be generated. Part of the steam is condensed by the colder components of the fuel channel and, finally, the steam pocket will reach one of the end fittings. The heating up process in the fuel channel will continue until the temperature in the end fitting will increase enough and no condensation will be possible. Subsequently, the steam will escape from that fuel channel. If the entire steam is vented from the fuel channel, the channel is refilled with cold water, received from the headers. The fuel sheath temperature is significantly reduced after the channel refill.

The maximum fuel sheath temperature for a maximum fuel channel power during normal operating conditions, for an initial water level of 0.9 m in the headers is presented in Figure 7. The maximum fuel sheath temperature predicted is about 560^0C while the maximum fuel pressure temperature was 510^0C (Figure 8). The temperatures predicted are slightly lower in case of an initial water level of 0.2 m in the headers.

Detailed fuel failure analyses show that the integrity of the fuel sheath is maintained during the 30 minutes transient.

4. Conclusions

Circuit analyses for a large LOCA event with loss of running ECC pump for 30 minutes at one day after the initiating Large LOCA event show moderate fuel sheath and pressure tube temperature increases. Similar temperature increases are predicted by the single channel analyses, higher temperatures being predicted for the core pass 3. Temperatures in core pass 4 are predicted lower due to presence of the break.

Conservative standing start / stagnant conditions imposed for a single fuel channel show that fuel sheath temperatures could increase up to a maximum of ~ 560^0C. For the same case, the pressure tube is not expected to exceed ~510^0C. Fuel sheath and pressure tube integrity are maintained during the stagnant flow conditions. Following restoration of the ECC pump operation, the fuel sheath and pressure tube temperatures are reduced to similar values, determined during the long term ECC stage operation and continuous fuel cooling is provided.

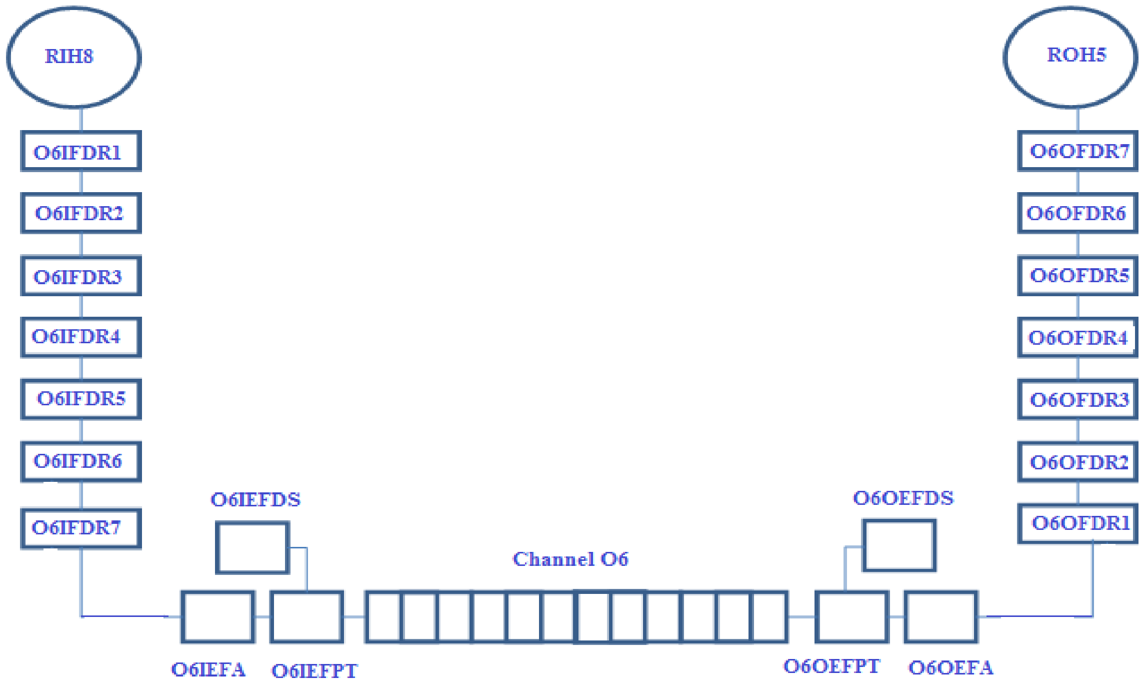

Figure 1 – Schematic diagram of the single channel model

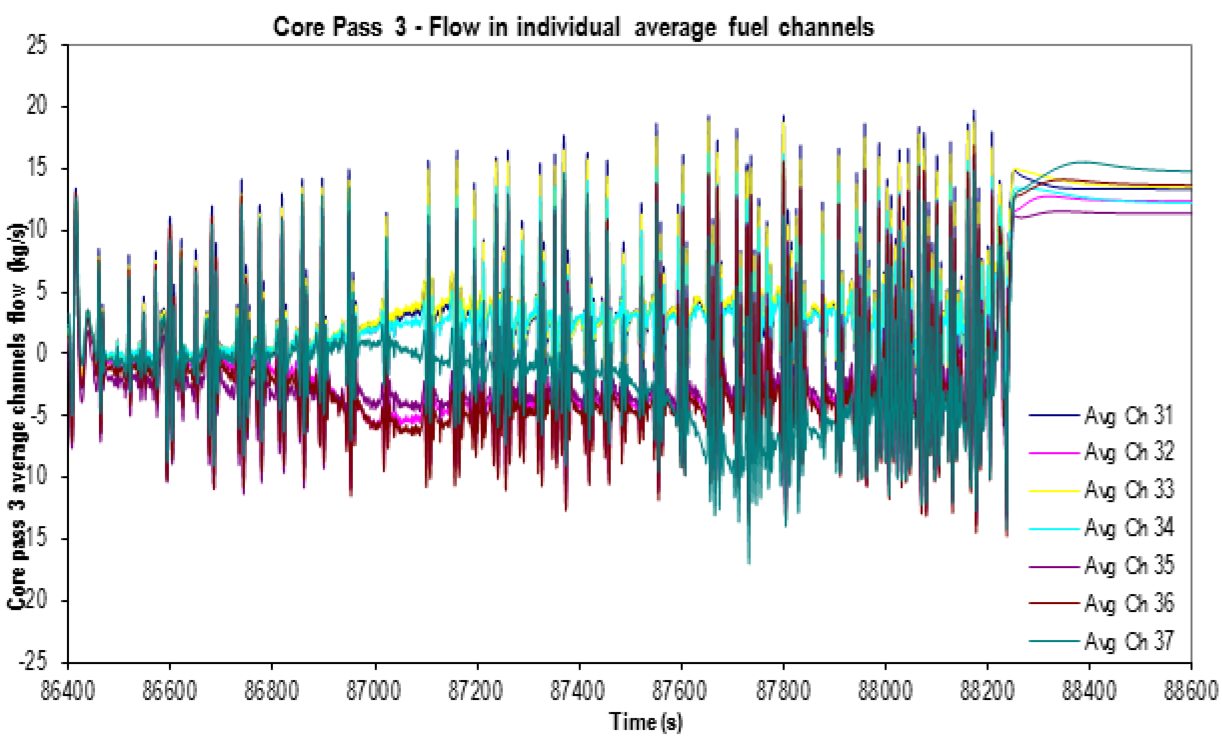

Figure 2- Core Pass 3 – Flow in Average Fuel Channels – Circuit analyses

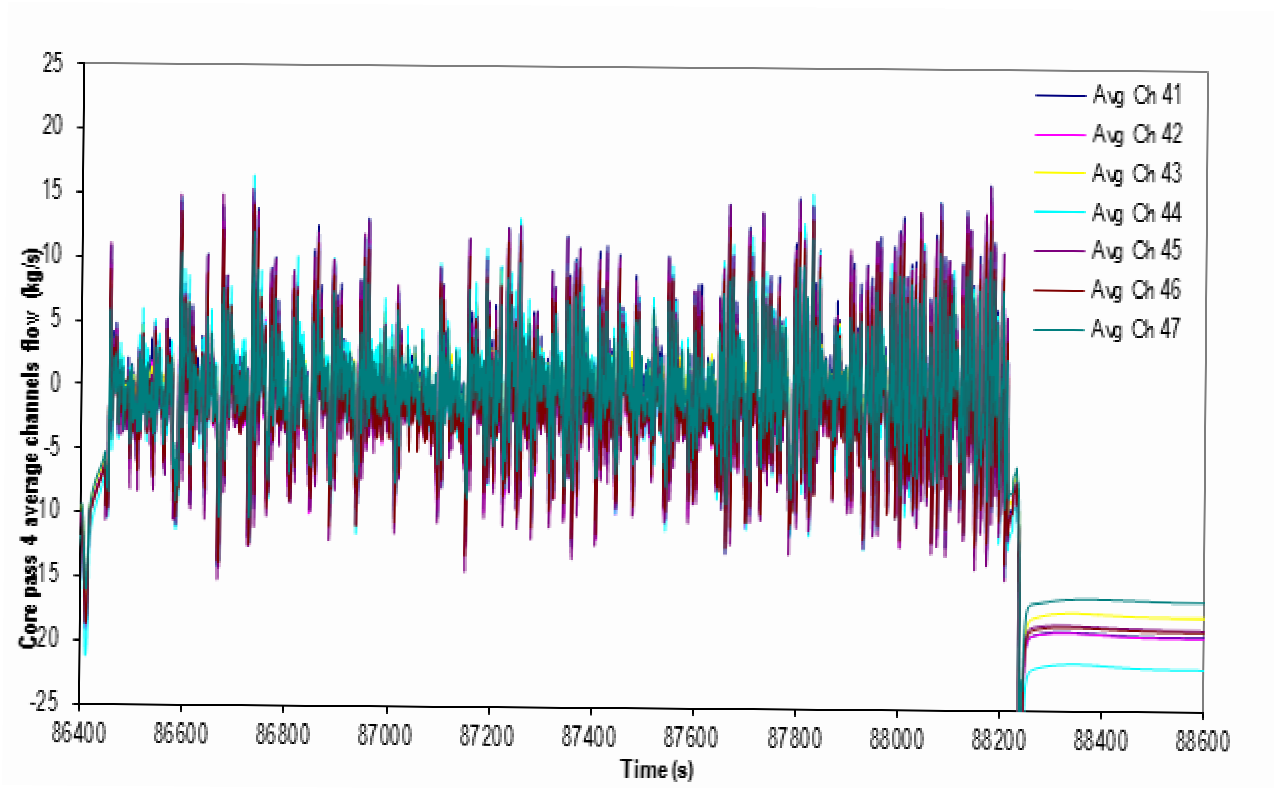

Figure 3 – Core pass 4 – Flow in Average Fuel Channels – Circuit analyses

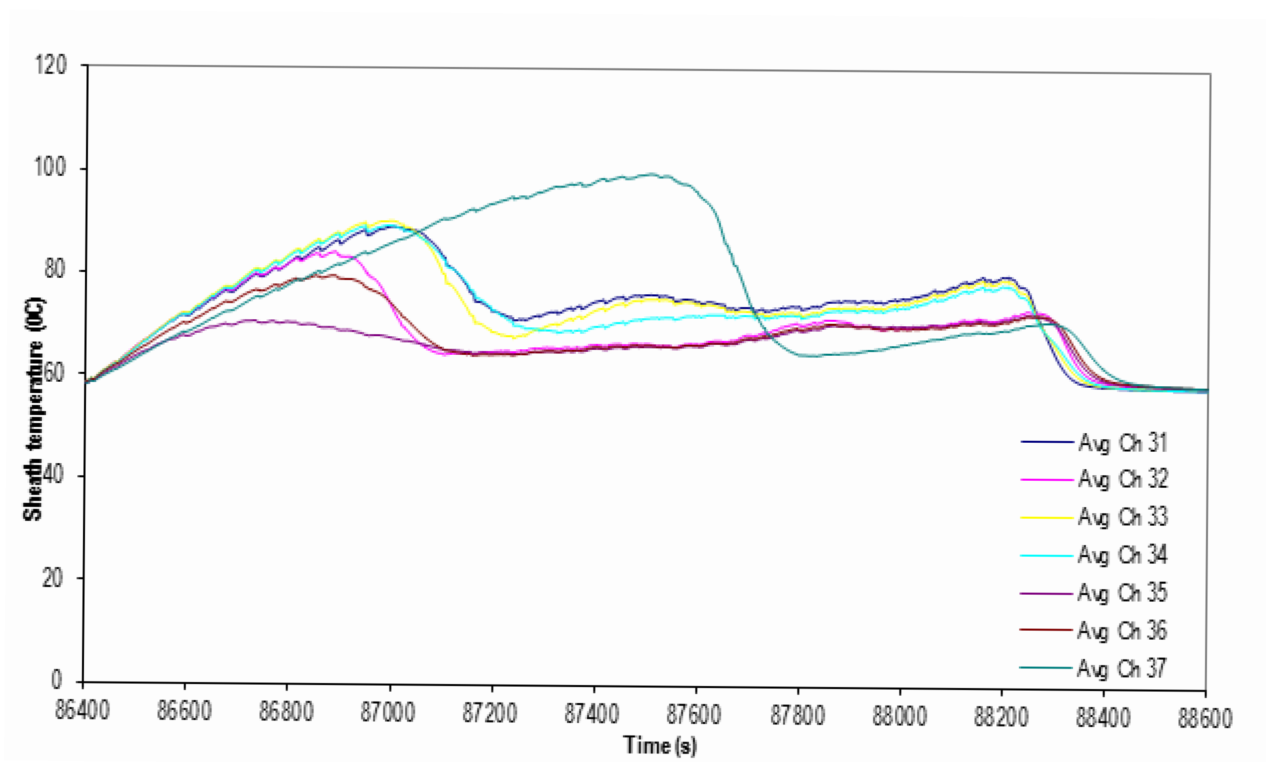

Figure 4 – Core pass 3 Fuel Sheath Temperature – Flow at 55 deg C during ECC LP Operation – Circuit Analyses

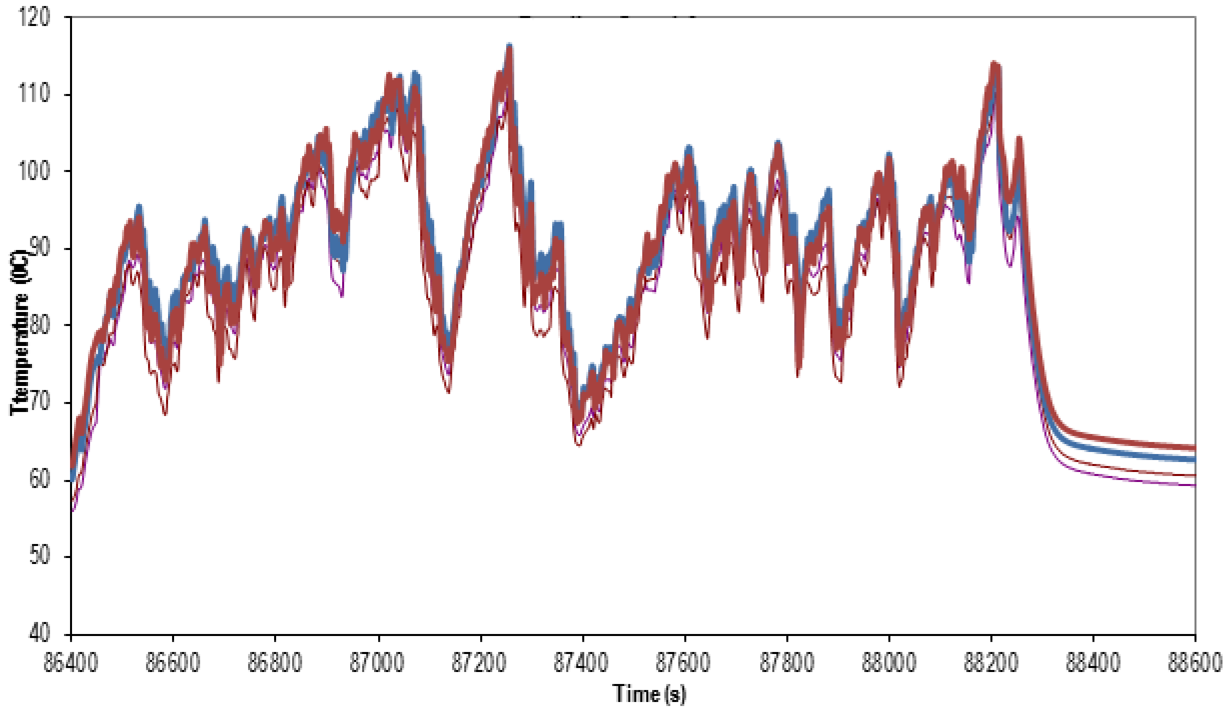

Figure 5 – Fuel Sheath / Pressure Tube Temperatures in Core Pass 3 – Single Channel Analyses

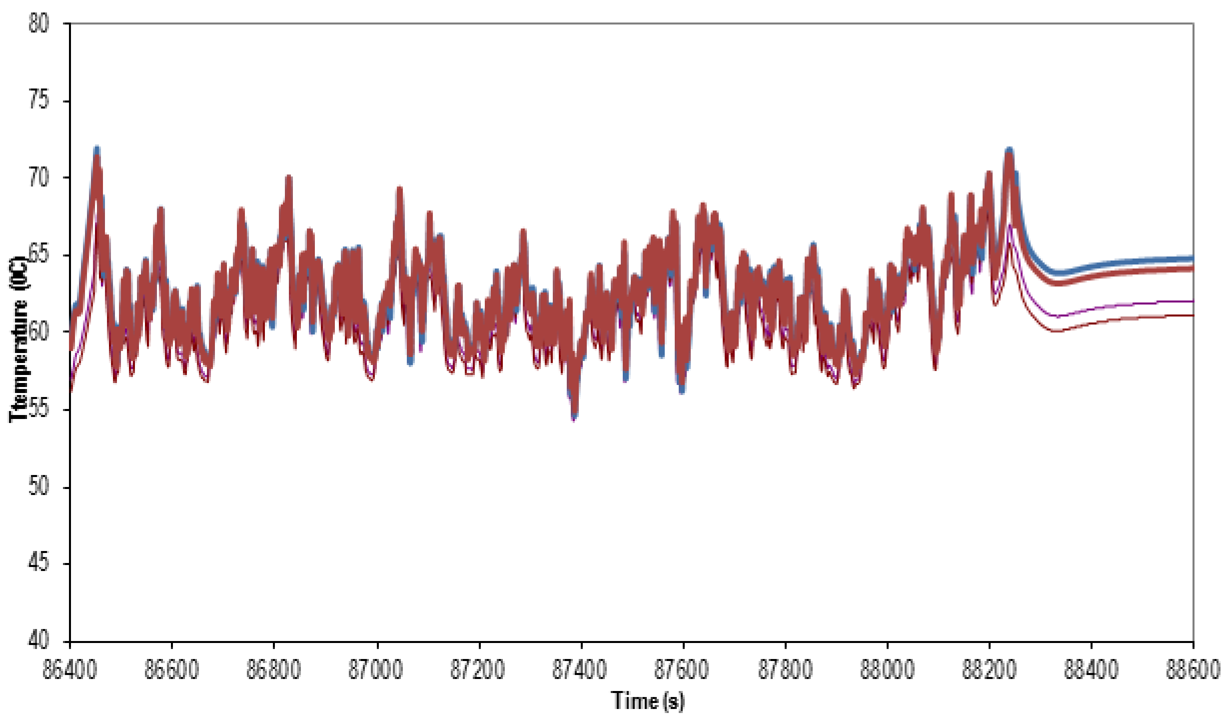

Figure 6 – Fuel Sheath / Pressure Tube Temperatures in Core Pass 4 – Single Channel Analyses

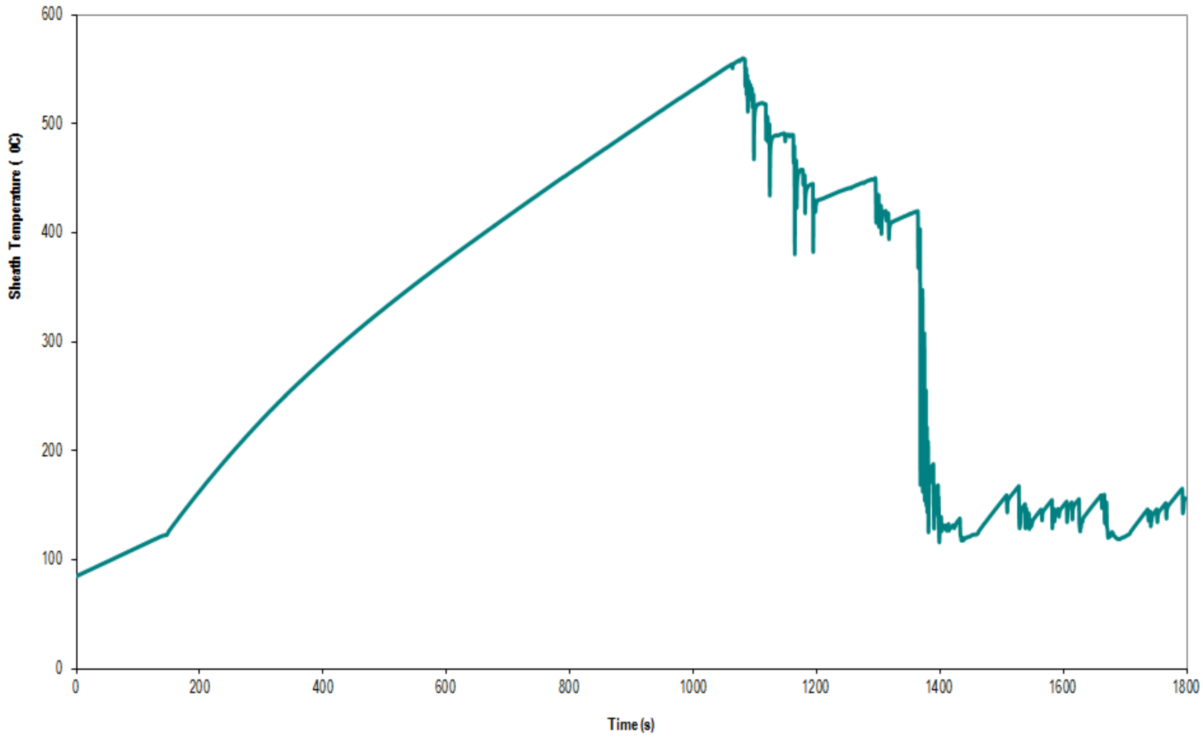

Figure 7 – Fuel Sheath Temperatures– Single Channel Analyses – Stagnant conditions

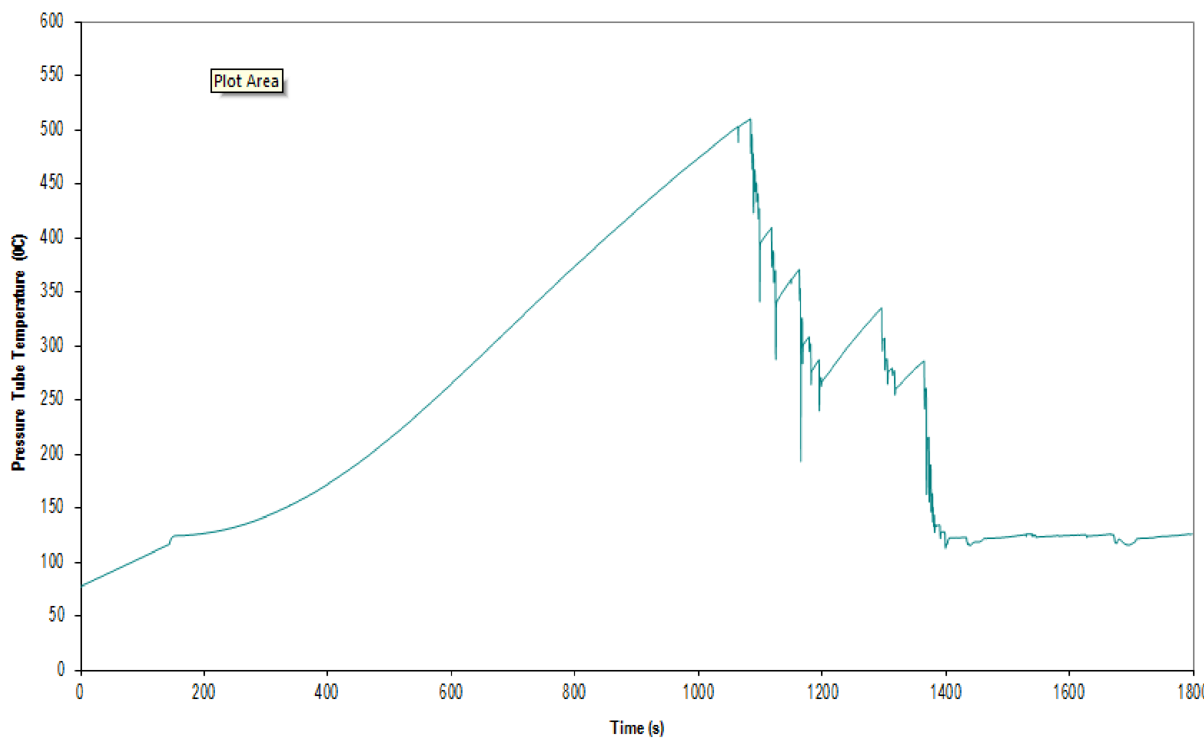

Figure 8 – Pressure Tube Temperatures– Single Channel Analyses – Stagnant conditions